12. B.B. Blinov, *et. al.,* UM HE 94-04, Submitted to Phys. Rev. Lett. (June 1994). Note that this first interpolation to 140 MeV of data on A at other energies was apparently too low in our polarimeter's angular range, since the polarization in the Cooler Ring clearly can not be larger than the injected polarization, which was about 75%. Thus there is a 15% normalization uncertainty in Figs. 2 and 3; fortunately, this normalization uncertainty does not affect the shape of the curves.
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COOLED BEAM INTENSITY LIMITS IN THE IUCF COOLER

Daniel Anderson, Mark S. Ball, Vladimir Derenchuk, Gary East, Michael J. Ellison, Tim Ellison, Brett J. Hamilton, Sergei S. Nagaitsev, and Peter Schwandt
Indiana University Cyclotron Facility, Bloomington Indiana 47408

The maximum cooled proton beam peak current stored in the IUCF Cooler at 45 MeV is about 6 mA (i.e., 6 mA coasting beam or about 1 mA for RF–bunched beams with bunching factors $[BF = I_{peak}/I_{ave}]$ of about 6). These currents have been obtained using a combination of stripping injection with electron cooling accumulation and transverse beam damping. This performance limitation is similar to that reported at other laboratories operating with similar beams:

- The LEAR ring has stored 5 mA of coasting beam using electron cooling and dampers.[1,2]
- CELSIUS has accumulated 2 mA using electron cooling accumulation and dampers.[3]

The *un-cooled* beam limit in the Cooler, however, may be 1 to 2 orders of magnitude higher. CELSIUS, for example, has accumulated and accelerated 40 mA (corresponding to a peak current of about 200 mA) using stripping injection *without* cooling[4] – about 40 times the maximum current stored at IUCF; the principal reason for this difference is the higher CELSIUS injector current, $\approx$ 75 μA of H_2^+ as compared to $\approx$ 0.75 μA of H_2^+ at IUCF.

Peak Current Limitation

As might be expected, the intensity limit in the IUCF Cooler is a peak current (I_{peak}) limit, rather than an average current (I_{ave}) limit. Since to first order we expect the bunch length to vary as $I_{ave}^{1/3}$ in the space-charge dominated regime[5,6] for a constant RF voltage, V_{rf}, it can be shown that for a constant peak current, I_{ave} should vary as $(h/V_{rf})^{1/2}$, where h is the harmonic number. Such is indeed the case in the Cooler, as illustrated in Fig. 1, where the measured maximum-achievable average stored-current is plotted as a function of the $h = 1$ RF voltage.

This suggests an operating mode that would increase I_{ave} without actually addressing the I_{peak} limit: for highly cooled beams, the balance between the space charge and RF

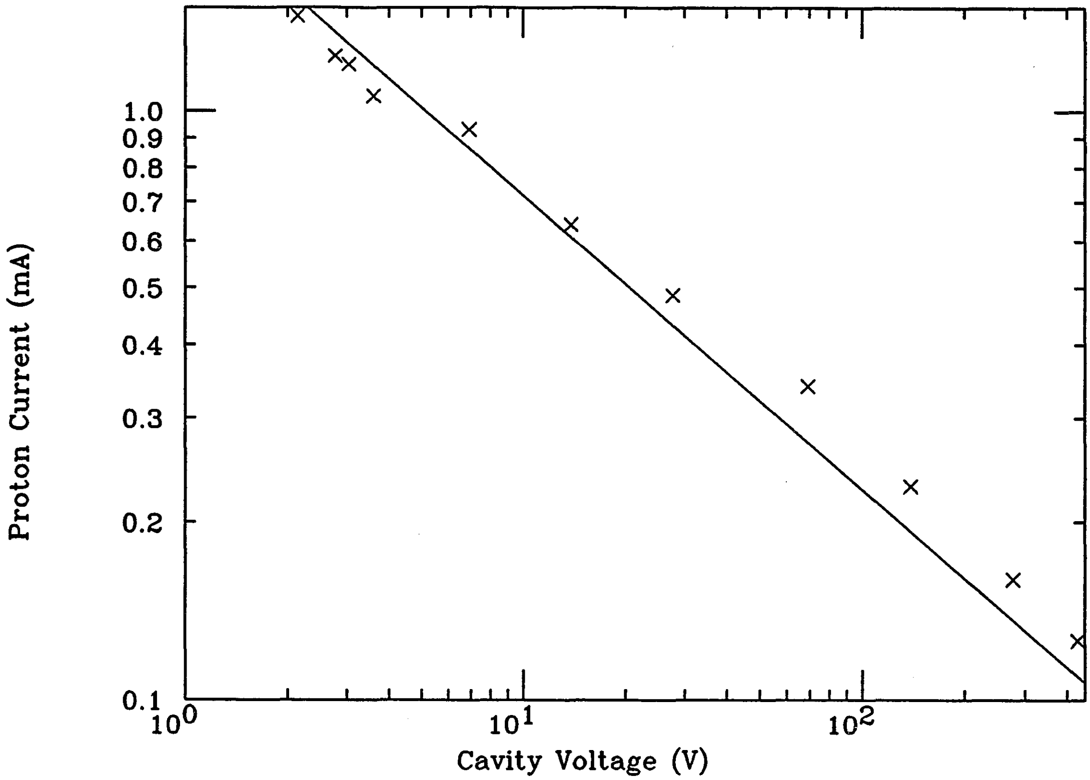

Figure 1. I_{ave} vs. V_{rf} (h=1) in the IUCF Cooler. Solid line is $V_{rf}^{1/2}$.

forces determines the required RF voltage for fixed frequency operation and the required energy gain per turn determines the voltage requirements during ramping. This is in contrast to the bucket area ($\propto h^{-1/2}$) requirements for emittance-dominated beams in many other machines. We thus operate in a regime where the required V_{rf} is not a function of h for beam acceleration, and should be able to increase I_{ave} by a factor of 2 to 3 by operating with a larger value for h (we presently operate at $h = 1$ for historical reasons). Instituting a "parabola" at the beginning of ramping would also lead to increased I_{ave} without increasing I_{limit}.

Coherent Transverse Instabilities

Although coherent transverse instabilities have been observed, they do not appear to be a limit:[7]

- Coherent transverse instabilities are usually observed only when the Cooler is operated in a non-standard mode (i.e., cooling the beam after injection for many seconds before beginning acceleration).
- A transverse feedback (damping) system can damp these instabilities at rates up to two orders of magnitude faster than the measured growth rates.

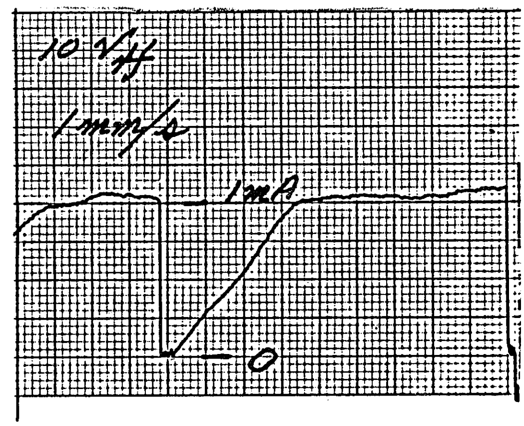

Figure 2. Beam current as a function of time during stripping injection with cooling accumulation.

Injection Efficiency

The I_{peak} limit is, within some constraints, independent of both the injected beam current and the injection repetition rate. We thus conclude that the limit is not related to beam lifetime. This is illustrated in Fig. 2, which shows the stored average current as a function of time during the process of cooling accumulation using stripping injection. The beam current does not increase as $I_{limit}(1 - e^{-t/\tau})$, where τ is the beam lifetime; rather the current increases with no significant change in rate until just below the limiting current. Beam is lost continuously between injections rather than suddenly; thus there is no indication of an easily-correctable hardware problem.

Beam Lifetime as a Function of Intensity

The manner in which the beam approaches its limiting current can be explained by the beam lifetime being a highly nonlinear function of the beam intensity. This is illustrated in Fig. 3, which shows the beam current as a function of time after the injection system is turned off.

Increased Transverse Beam Size

One could conjecture that the intensity limit is due to an increase in the beam size with increasing current. This conjecture is supported by the observed large decrease in the geometrical constant g[5], which is proportional to the natural logarithm of the ratio of the vacuum chamber radius to the beam radius for a centered beam inside a round pipe, as shown in Fig. 4. This conjecture was tested by measuring the effective ring aperture as a function of beam current by exciting a coherent betatron oscillation with the injection kicker and observing the percentage loss of beam. The results, shown in Fig. 5, however, seem to indicate the opposite: that the effective aperture *increases* with beam current! There is no explanation for this observation; we do know, however, that at high currents the de-coherence of both longitudinal and transverse coherent oscillations is suppressed, and thus the beam behaves significantly different in the low and high current regimes when a coherent oscillation is excited.

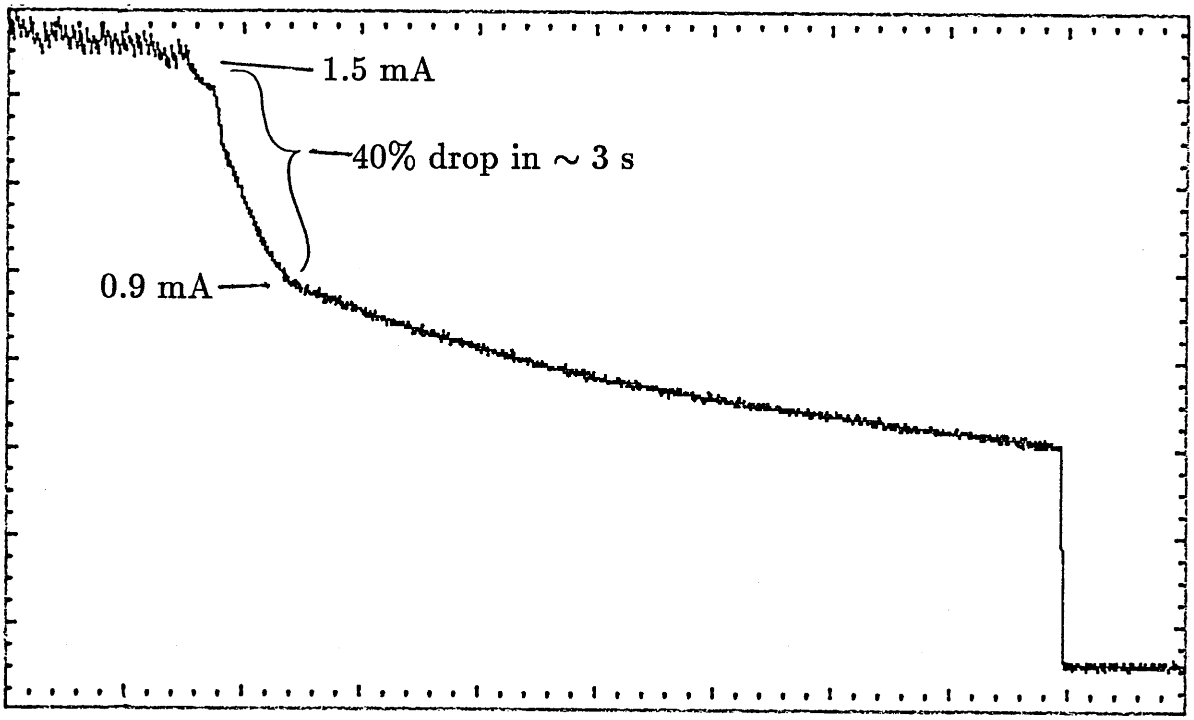

Figure 3. Beam current as a function of time after the injection system is turned off.

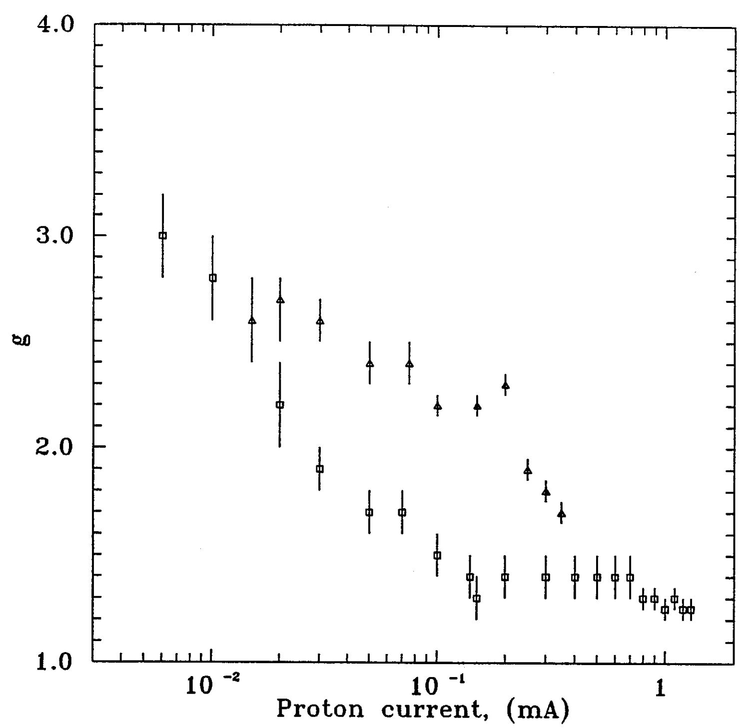

Figure 4. Geometrical constant g as a function of current.

Recent measurements[8] of the transverse beam size as a function of beam current indicate that even at high currents the non-normalized rms beam emittance ($\approx 0.1\pi\ \mu$m) is still only a small fraction of the ring acceptance, ($\approx 10\pi\ \mu$m). At currents close to the intensity limit, however, the transverse beam distribution begins to develop very long tails – up to 8 times the width of the rms size of the bright core[8] (corresponding to an emittance 64 times greater than the rms emittance). We suspect that these tails are related to the beam intensity limit.

Space Charge Effects

The limit appears to be due to space-charge effects. Space-charge effects in synchrotrons are usually quantified by the space-charge tune shift, ΔQ_{SC} which can be expressed as:

$$\Delta Q_{SC} = \frac{BF \cdot I_{ave} C r_p}{4\pi e c \beta^2 \gamma^2 \epsilon_N} \tag{1}$$

where C is the ring circumference, r_p is the classical proton radius, e is the proton charge, c is the speed of light, β and γ are the usual relativistic parameters, and ϵ_N is the normalized rms beam emittance. ΔQ_{SC} is the amount the incoherent betatron tune is reduced due to defocussing effects from the beam space charge. We note that ΔQ_{SC} is not directly measured; in this case the tune shift is a mathematical quantity that can be exactly calculated but does not necessarily accurately represent what is happening physically.

The equilibrium horizontal transverse profile and beta function at the profile monitor location (to determine ϵ_N) and the equilibrium longitudinal bunch shape (to determine $BF \cdot I_{ave}$) have recently been measured in the IUCF Cooler as a function of the 45 MeV proton beam current. Fig. 6 shows the calculated space-charge tune shift as a function of proton beam current.

It is easy to understand how a large ΔQ_{SC} can lead to emittance growth: the small amplitude particles, which have the largest tune shift, can be shifted onto a major resonance line. It is less easy to understand why instead the high tune shifts should lead to a beam loss. It may be that the particles with high amplitudes are lost; these particles experience a smaller tune shift, but also experience more nonlinear fields from the beam space charge which may drive higher order resonances.

We have observed that very small (< 0.01) changes in the coherent betatron tunes can make greater than order of magnitude changes in the equilibrium beam intensity; this is somewhat unexpected for situations in which the incoherent tune shift is presumed to be more than an order of magnitude larger.

Conclusion

We have just begun to explore means for increasing the stored beam current. Thus far, we have identified no techniques that can substantially increase the limiting beam current without compromising our ability to accumulate beam quickly. In January, 1994 we started to explore the beam transverse equilibrium systematically using a flying wire profile monitor; the information from this monitor should answer many of our questions. In the meantime, we are beginning to take more seriously the possibility of drilling a small hole in the center of the cathode!

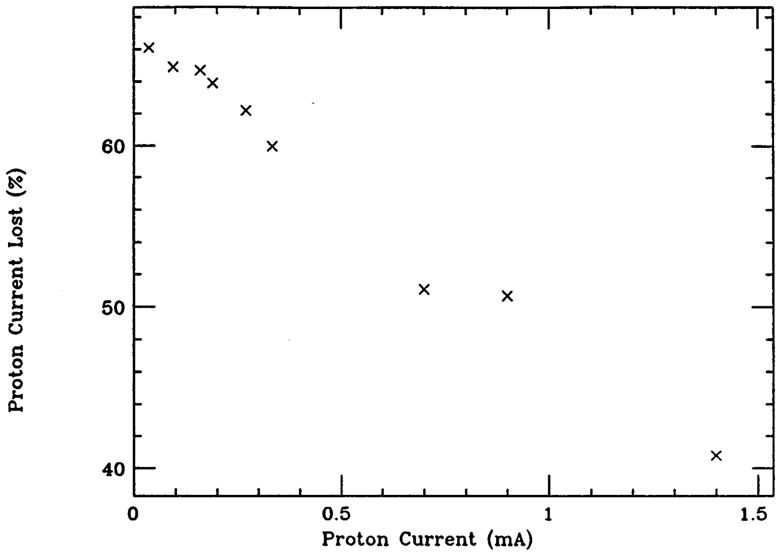

Figure 5. Percentage beam loss as a function of beam current for a fixed kicker strength corresponding to 10π μm (non-normalized).

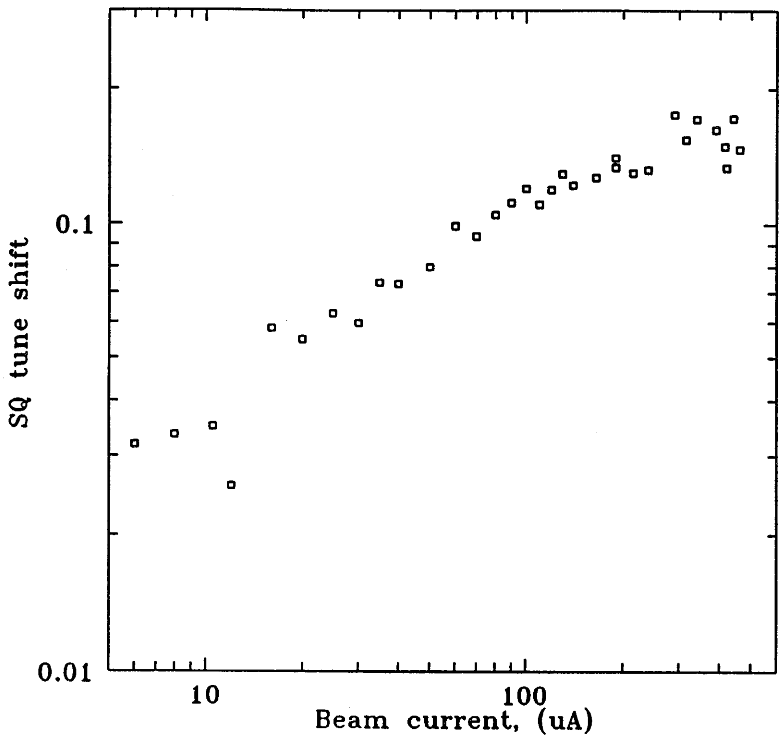

Figure 6. Space charge tune shift as a function of proton beam current.

1. Jacques Bosser, CERN (private communication: FAX's 14 and 15 January 1993); a maximum of 3 mA had been stored in the LEAR ring.
2. Gerard Tranquille, CERN (private communication, E-mail 15 March 1994); a record of 5 mA had been achieved.
3. Dag Reistad, CELSIUS (private telephone communication 11 March 1993).
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5. S. Nagaitsev, T. Ellison, M. Ellison, D. Anderson, in the *Proceedings of the 1993 Workshop on Beam Cooling*, October 3–8, 1993, Montreux, Switzerland.
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8. D. Anderson, M. Ball, V. Derenchuk, G. East, M. Ellison, T. Ellison, B. Hamilton, S. Nagaitsev, P. Schwandt, in this report.

THE INVESTIGATION OF SPACE CHARGE DOMINATED BEAMS IN A SYNCHROTRON

S. Nagaitsev, D. Anderson, M. Ball, V. Derenchuk, G. East,
T. Ellison, M. Ellison, B. Hamilton, and P. Schwandt
Indiana University Cyclotron Facility, Bloomington, Indiana 47408

Knowledge of the longitudinal momentum spread of an electron-cooled proton beam is important for experiments which rely upon the unique properties of this beam. Since the RF cavity produces a conservative force, it cannot change the beam longitudinal phase density. Consequently, for a known RF voltage, the beam time spread normally provides a direct measurement of the beam momentum spread. An electron-cooling system,[1] however, can reduce the ion beam emittance to extremely small values. In this regime the ion beam, interacting with its surrounding, generates longitudinal self-fields which significantly modify, and in fact to first order determine, the bunch shape.[2] It can be shown that for the ion beams below transition, the most significant part of this interaction comes from the electrostatic repulsion between the ions within the bunch. Since in all cases of interest the bunch lengths are much greater than the radius of the surrounding vacuum chamber, one can treat the beam as a thin thread and reduce the electrostatic problem to one dimension. The Vlasov technique can then be used to find the self-consistent longitudinal particle distribution function.[3]

For electron-cooled ion beams, however, one needs to modify the Vlasov equation to include both damping and diffusion.[4] Although the cooling force is generally a complex function of proton momentum,[5] it can be approximated well as a linear function of relative proton momentum, δ, for δ smaller than the longitudinal relative momentum spread of the